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14. ABSTRACT
During the full period of this project we have (1) demonstrated room-temperature effects of the remanent magnetization from electrically-isolated magnetic films on the conductivity and electroluminescence of organic devices, (2) developed and applied a percolation theory of magnetoresistance to describe magnetic field effects on spin transport in organic semiconductors, (3) discovered and theoretically explained the effects of traps and unpaired spins on room-temperature magnetoresistance, (4) developed a theory for spin diffusion in hopping transport due to hyperfine interaction and spin-orbit interaction, (5) predicted and measured spatial interference

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## Report Title

Final Report: Room-Temperature Spin-Mediated Coupling in Hybrid Magnetic, Organic, and Oxide Structures and Devices

## ABSTRACT

During the full period of this project we have (1) demonstrated room-temperature effects of the remanent magnetization from electrically-isolated magnetic films on the conductivity and electroluminescence of organic devices, (2) developed and applied a percolation theory of magnetoresistance to describe magnetic field effects on spin transport in organic semiconductors, (3) discovered and theoretically explained the effects of traps and unpaired spins on room-temperature magnetoresistance, (4) developed a theory for spin diffusion in hopping transport due to hyperfine interaction and spin-orbit interaction, (5) predicted and measured spatial interference patterns from multiple coherent spin torque oscillators, (6) predicted spin-wave dispersion relations in magnonic crystals, (7) predicted electric-field control of spin-wave propagation velocities and interferometers, (8) developed a theory for spin lifetimes and spin Hall conductivities for oxide two-dimensional electron gases, (9) measured spin-orbit interactions in nanoscale wires in oxide semiconductor interfaces, (10) demonstrated electrical control of ferromagnetism in the LAO/STO system, (11) demonstrated hybrid organic/inorganic spin valves, (12) developed interfacial magnetic systems based on oxide superlattices, and (13) demonstrated GHz operation of sketched oxide transistors at the LAO/STO interface.

**Enter List of papers submitted or published that acknowledge ARO support from the start of the project to the date of this printing. List the papers, including journal references, in the following categories:**

**(a) Papers published in peer-reviewed journals (N/A for none)**

| Received | | Paper |
|---|---|---|
| 08/31/2011 | 2.00 | G. Vignale, Tianyu Liu. Electric Control of Spin Currents and Spin-Wave Logic, Physical Review Letters, (6 2011): 0. doi: 10.1103/PhysRevLett.106.247203 |
| 08/31/2011 | 16.00 | Cheng Cen, Daniela F Bogorin, Jeremy Levy. Thermal activation and quantum field emission in a sketch-based oxide nanotransistor, Nanotechnology, (12 2010): 475201. doi: |
| 08/31/2011 | 13.00 | Guanglei Cheng, Pablo F. Siles, Feng Bi, Cheng Cen, Daniela F. Bogorin, Chung Wung Bark, Chad M. Folkman, Jae-Wan Park, Chang-Beom Eom, Gilberto Medeiros-Ribeiro, Jeremy Levy. Sketched oxide single-electron transistor, Nature Nanotechnology, (06 2011): 343. doi: |
| 08/31/2011 | 12.00 | Fujian Wang, James Rybicki, Ran Lin, Kent A. Hutchinson, Jia Hou, Markus Wohlgenannt. Frequency dependence of organic magnetoresistance, Synthetic Metals, (05 2011): 622. doi: |
| 08/31/2011 | 11.00 | Ran Lin, Fujian Wang, Markus Wohlgenannt, Chunyong He, Xiaofang Zhai, Yuri Suzuki. Organic spin-valves based on fullerene C60, Synthetic Metals, (04 2011): 553. doi: |
| 08/31/2011 | 9.00 | F. Macia, A. D. Kent, F. C. Hoppensteadt. Anisotropic spin-wave patterns generated by spin-torque nano-oscillators, Journal of Applied Physics, (04 2011): 73733. doi: |
| 08/31/2011 | 8.00 | Ferran Macià, Andrew D Kent, Frank C Hoppensteadt. Spin-wave interference patterns created by spin-torque nano-oscillators for memory and computation, Nanotechnology, (03 2011): 0. doi: 10.1088/0957-4484/22/9/095301 |
| 08/31/2011 | 6.00 | F. Wang, J. Rybicki, K. Hutchinson, M. Wohlgenannt. Magnetic-field effect in organic photoconductive devices studied by time-of-flight, Physical Review B, (6 2011): 0. doi: 10.1103/PhysRevB.83.241202 |
| 08/31/2012 | 17.00 | Daniela F. Bogorin, Feng Bi, Cheng Cen, Chung Wung Bark, Jae-Wan Park, Chang-Beom Eom, Jeremy Levy. “Water-cycle” mechanism for writing and erasing nanostructures at the LaAlO3/SrTiO3 interface, Applied Physics Letters, (10 2010): 173110. doi: |
| 08/31/2012 | 48.00 | M. Flatté, N. Harmon. Spin-Flip Induced Magnetoresistance in Positionally Disordered Organic Solids, Physical Review Letters, (05 2012): 0. doi: 10.1103/PhysRevLett.108.186602 |
| 08/31/2012 | 47.00 | Brian T. Collins, Michael E. Flatté, Jian-Ming Tang. Electron spin-phonon interaction symmetries and tunable spin relaxation in silicon and germanium, Physical Review B, (01 2012): 0. doi: 10.1103/PhysRevB.85.045202 |
| 08/31/2012 | 46.00 | N. Harmon, M. Flatté. Effects of spin-spin interactions on magnetoresistance in disordered organic semiconductors, Physical Review B, (06 2012): 0. doi: 10.1103/PhysRevB.85.245213 |

08/31/2012 45.00 N. Harmon, M. Flatté. Semiclassical theory of magnetoresistance in positionally disordered organic semiconductors,
Physical Review B, (02 2012): 0. doi: 10.1103/PhysRevB.85.075204

08/31/2012 43.00 Oleg Chalaev, G. Vignale, Michael E. Flatté. Spin-orbit interaction from low-symmetry localized defects in semiconductors,
EPL (Europhysics Letters), (04 2012): 0. doi: 10.1209/0295-5075/98/17013

08/31/2012 41.00 Tianyu Liu, G. Vignale. Flexoelectric phase shifter for spin waves,
Journal of Applied Physics, (04 2012): 0. doi: 10.1063/1.4703925

08/31/2012 39.00 F. J. Wong, E. Arenholz, A. Vailionis, Y. Suzuki, A. J. Grutter. Evidence of high-spin Ru and universal magnetic anisotropy in SrRuO_{3} thin films,
Physical Review B, (04 2012): 0. doi: 10.1103/PhysRevB.85.134429

08/31/2012 38.00 C. He, T. Sanders, M. Gray, F. Wong, V. Mehta, Y. Suzuki. Metal-insulator transitions in epitaxial LaVO_{3} and LaTiO_{3} films,
Physical Review B, (08 2012): 0. doi: 10.1103/PhysRevB.86.081401

08/31/2012 36.00 Markus Wohlgenannt. Organic magnetoresistance and spin diffusion in organic semiconductor thin film devices,
physica status solidi (RRL) - Rapid Research Letters, (06 2012): 0. doi: 10.1002/pssr.201206129

08/31/2012 34.00 Fujian Wang, Ferran Macià, Markus Wohlgenannt, Andrew Kent, Michael Flatté. Magnetic Fringe-Field Control of Electronic Transport in an Organic Film,
Physical Review X, (06 2012): 0. doi: 10.1103/PhysRevX.2.021013

08/31/2012 33.00 Andrew D. Kent, Hideo Ohno, Arne Brataas. Current-induced torques in magnetic materials,
Nature Materials, (04 2012): 0. doi: 10.1038/nmat3311

08/31/2012 32.00 F. Macia↑, P. Warnicke, D. Bedau, M.-Y. Im, P. Fischer, D.A. Arena, A.D. Kent. Perpendicular magnetic anisotropy in ultrathin Co|Ni multilayer films studied with ferromagnetic resonance and magnetic x-ray microspectroscopy,
Journal of Magnetism and Magnetic Materials, (03 2012): 3629. doi:

08/31/2013 50.00 Nicholas J. Harmon, Michael E. Flatté. Theory of Organic Magnetoresistance in Disordered Organic Semiconductors,
SPIE: Optics+Photonics, (08 2012): 1. doi:

08/31/2013 51.00 F. Macià, F. Wang, N. J. Harmon, M. Wohlgenannt, A. D. Kent, M. E. Flatté. Hysteretic control of organic conductance due to remanent magnetic fringe fields,
Applied Physics Letters, (02 2013): 0. doi: 10.1063/1.4790141

08/31/2013 52.00 N. J. Harmon, F. Macià, F. Wang, M. Wohlgenannt, A. D. Kent, M. E. Flatté. Including fringe fields from a nearby ferromagnet in a percolation theory of organic magnetoresistance,
Physical Review B, (03 2013): 0. doi: 10.1103/PhysRevB.87.121203

08/31/2013 53.00 Lorien X. Hayden, R. Raimondi, M. E. Flatté, G. Vignale. Intrinsic spin Hall effect at asymmetric oxide interfaces: Role of transverse wave functions,
Physical Review B, (08 2013): 0. doi: 10.1103/PhysRevB.88.075405

08/31/2013 54.00 N. J. Harmon, M. E. Flatté. Distinguishing Spin Relaxation Mechanisms in Organic Semiconductors,
Physical Review Letters, (04 2013): 0. doi: 10.1103/PhysRevLett.110.176602

08/31/2013 55.00 J. Rybicki, R. Lin, F. Wang, M. Wohlgenannt, C. He, T. Sanders, Y. Suzuki. Tuning the Performance of Organic Spintronic Devices Using X-Ray Generated Traps,
Physical Review Letters, (08 2012): 0. doi: 10.1103/PhysRevLett.109.076603

08/31/2013 56.00 Joshua P. Veazey, Guanglei Cheng, Patrick Irvin, Shicheng Lu, Chung-Wung Bark, Sangwoo Ryu, Chang-Beom Eom, Jeremy Levy. Anomalous High Mobility in LaAlO,
Nano Letters, (02 2013): 0. doi: 10.1021/nl3033729

08/31/2013 57.00 Guanglei Cheng, Joshua P. Veazey, Patrick Irvin, Cheng Cen, Daniela F. Bogorin, Feng Bi, Mengchen Huang, Shicheng Lu, Chung-Wung Bark, Sangwoo Ryu, Kwang-Hwan Cho, Chang-Beom Eom, Jeremy Levy. Anomalous Transport in Sketched Nanostructures at the LaAlO_{3}/SrTiO_{3} Interface,
Physical Review X, (03 2013): 0. doi: 10.1103/PhysRevX.3.011021

08/31/2013 58.00 P. Irvin, M. Huang, F. J. Wong, T. D. Sanders, Y. Suzuki, J. Levy. Gigahertz-frequency operation of a LaAlO3/SrTiO3-based nanotransistor,
Applied Physics Letters, (03 2013): 0. doi: 10.1063/1.4795725

08/31/2013 60.00 C. He, A. J. Grutter, M. Gu, N. D. Browning, Y. Takamura, B. J. Kirby, J. A. Borchers, J. W. Kim, M. R. Fitzsimmons, X. Zhai, V. V. Mehta, F. J. Wong, Y. Suzuki. Interfacial Ferromagnetism and Exchange Bias in CaRuO_{3}/CaMnO_{3} Superlattices,
Physical Review Letters, (11 2012): 0. doi: 10.1103/PhysRevLett.109.197202

08/31/2013 61.00 M. T. Gray, T. D. Sanders, F. J. Wong, A. J. Grutter, U. S. Alaan, C. He, C. A. Jenkins, E. Arenholz, Y. Suzuki. Quasi-two-dimensional electron gas behavior in doped LaAlO3 thin films on SrTiO3 substrates,
Applied Physics Letters, (04 2013): 0. doi: 10.1063/1.4800232

09/01/2011 19.00 Franklin Wong, Rajesh Chopdekar, Yuri Suzuki. Disorder and localization at the LaAlO_{3}/SrTiO_{3} heterointerface,
Physical Review B, (10 2010): 0. doi: 10.1103/PhysRevB.82.165413

09/01/2011 20.00 C. He, X. Zhai, V. V. Mehta, F. J. Wong, Y. Suzuki. Interfacial magnetism in CaRuO3/CaMnO3 superlattices grown on (001) SrTiO3,
Journal of Applied Physics, (04 2011): 74729. doi:

09/04/2012 37.00 F. J. Wong, A. J. Grutter, J. M. Iwata-Harms, V. V. Mehta, U. S. Alaan, E. Arenholz, Y. Suzuki. Structure and magnetism of nanocrystalline and epitaxial (Mn,Zn,Fe)3O4 thin films,
Journal of Applied Physics, (02 2012): 0. doi: 10.1063/1.3676619

09/04/2012 40.00 Franklin J. Wong, Shaobo Zhu, Jodi M. Iwata-Harms, Yuri Suzuki. Electronic tuning of La2/3Sr1/3MnO3 thin films via heteroepitaxy,
Journal of Applied Physics, (03 2012): 0. doi: 10.1063/1.3699047

12/05/2011 24.00 E. A. Golovatski, M. E. Flatté. Spin torque and charge resistance of ferromagnetic semiconductor 2pi and pi domain walls,
Physical Review B, (9 2011): 0. doi: 10.1103/PhysRevB.84.115210

12/05/2011 25.00 Ionel Tifrea, Michael Flatté. Nonequilibrium nuclear polarization and induced hyperfine and dipolar magnetic fields in semiconductor nanostructures,
Physical Review B, (10 2011): 0. doi: 10.1103/PhysRevB.84.155319

12/06/2015 62.00 N. J. Harmon, M. E. Flatté. Organic magnetoresistance from deep traps,
Journal of Applied Physics, (07 2014): 43707. doi: 10.1063/1.4891476

12/06/2015 63.00 Ferran Macià, Fujian Wang, Nicholas J. Harmon, Andrew D. Kent, Markus Wohlgenannt, Michael E. Flatté. Organic magnetoelectroluminescence for room temperature transduction between magnetic and optical information,
Nature Communications, (04 2014): 3609. doi: 10.1038/ncomms4609

12/06/2015 64.00 Y. Wang, N. J. Harmon, K. Sahin-Tiras, M. Wohlgenannt, M. E. Flatté. Anomalous organic magnetoresistance from competing carrier-spin-dependent interactions with localized electronic and nuclear spins,
Physical Review B, (08 2014): 60204. doi: 10.1103/PhysRevB.90.060204

12/06/2015 65.00 Giovanni Vignale, Michael E. Flatté, Cüneyt Sahin. Derivation of effective spin-orbit Hamiltonians and spin lifetimes with application to,
Physical Review B, (04 2014): 155402. doi: 10.1103/PhysRevB.89.155402

12/06/2015 66.00 N. J. Harmon, M. E. Flatté. Spin relaxation in materials lacking coherent charge transport,
Physical Review B, (09 2014): 115203. doi: 10.1103/PhysRevB.90.115203

12/06/2015 67.00 Marco Polini, Giovanni Vignale, Amit Agarwal, Michael E. Flatté. Long-lived spin plasmons in a spin-polarized two-dimensional electron gas,
Physical Review B, (10 2014): 155409. doi: 10.1103/PhysRevB.90.155409

12/06/2015 68.00 Mengchen Huang, Hyungwoo Lee, Chang-Beom Eom, Patrick Irvin, Jeremy Levy, Feng Bi. LaAlO3 thickness window for electronically controlled magnetism at LaAlO3/SrTiO3 heterointerfaces,
Applied Physics Letters, (08 2015): 82402. doi: 10.1063/1.4929430

12/06/2015 69.00 Guanglei Cheng, Michelle Tomczyk, Shicheng Lu, Joshua P. Veazey, Mengchen Huang, Patrick Irvin, Sangwoo Ryu, Hyungwoo Lee, Chang-Beom Eom, C. Stephen Hellberg, Jeremy Levy. Electron pairing without superconductivity,
Nature, (05 2015): 196. doi: 10.1038/nature14398

12/06/2015 70.00 Mengchen Huang, Sangwoo Ryu, Hyungwoo Lee, Chung-Wung Bark, Chang-Beom Eom, Patrick Irvin, Jeremy Levy, Feng Bi. Room-temperature electronically-controlled ferromagnetism at the LaAlO3/SrTiO3 interface,
Nature Communications, (09 2014): 5019. doi: 10.1038/ncomms6019

12/06/2015 72.00 Shahal Ilani, Patrick Irvin, Jeremy Levy, Joseph A. Sulpizio. Nanoscale Phenomena in Oxide Heterostructures,
Annual Review of Materials Research, (07 2014): 117. doi: 10.1146/annurev-matsci-070813-113437

12/06/2015 71.00 Akash Levy, Feng Bi, Mengchen Huang, Shicheng Lu, Michelle Tomczyk, Guanglei Cheng, Patrick Irvin, Jeremy Levy. Writing and Low-Temperature Characterization of Oxide Nanostructures,
Journal of Visualized Experiments, (07 2014): 51886. doi: 10.3791/51886

12/06/2015 73.00 Joshua P Veazey, Guanglei Cheng, Patrick Irvin, Cheng Cen, Daniela F Bogorin, Feng Bi, Mengchen Huang, Chung-Wung Bark, Sangwoo Ryu, Kwang-Hwan Cho, Chang-Beom Eom, Jeremy Levy. Oxide-based platform for reconfigurable superconducting nanoelectronics,
Nanotechnology, (09 2013): 375201. doi: 10.1088/0957-4484/24/37/375201

12/06/2015 74.00 J. P. Veazey, G. Cheng, S. Lu, M. Tomczyk, F. Bi, M. Huang, S. Ryu, C. W. Bark, K. H. Cho, C. B. Eom, P. Irvin, J. Levy. Nonlocal current-voltage characteristics of gated superconducting sketched oxide nanostructures,
EPL (Europhysics Letters), (09 2013): 57001. doi: 10.1209/0295-5075/103/57001

12/06/2015 75.00 D. Backes, F. Macià, S. Bonetti, R. Kukreja, H. Ohldag, A.?D. Kent. Direct Observation of a Localized Magnetic Soliton in a Spin-Transfer Nanocontact,
Physical Review Letters, (09 2015): 127205. doi: 10.1103/PhysRevLett.115.127205

12/07/2015 77.00 Dirk Backes, Andrew D. Kent, Ferran Macià. Stable magnetic droplet solitons in spin-transfer nanocontacts,
Nature Nanotechnology, (11 2014): 992. doi: 10.1038/nnano.2014.255

12/07/2015 78.00 F Macià, F C Hoppensteadt, A D Kent. Spin wave excitation patterns generated by spin torque oscillators,
Nanotechnology, (01 2014): 45303. doi: 10.1088/0957-4484/25/4/045303

12/07/2015 79.00 T. D. Sanders, M. T. Gray, F. J. Wong, Y. Suzuki. interfaces doped with rare-earth ions,
Physical Review B, (05 2015): 205112. doi: 10.1103/PhysRevB.91.205112

12/07/2015 80.00 A. J. Grutter, F. J. Wong, C. A. Jenkins, E. Arenholz, A. Vailionis, Y. Suzuki. Stabilization of spin-zero Ru 4+ through epitaxial strain in SrRuO3 thin films,
Physical Review B, (12 2013): 214410. doi: 10.1103/PhysRevB.88.214410

12/07/2015 81.00 Markus Wohlgenannt, Peter A. Bobbert, Bert Koopmans. Intrinsic magnetic field effects in organic semiconductors,
MRS Bulletin, (07 2014): 590. doi: 10.1557/mrs.2014.132

**TOTAL: 57**

**Number of Papers published in peer-reviewed journals:**

## (b) Papers published in non-peer-reviewed journals (N/A for none)

| Received | Paper |
|---|---|
| 12/07/2015 76.00 | M. Wohlgenannt, M. E. Flatté, N. J. Harmon, F. Wang, A. D. Kent, F. Macià2. Singlet-to-triplet interconversion using hyperfine as well as ferromagnetic fringe fields, Phil. Trans. Roy. Soc. A, (04 2015): 20140326. doi: |
| **TOTAL:** | **1** |

**Number of Papers published in non peer-reviewed journals:**

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## (c) Presentations

"Real-Time Transport Properties of Multiply-Connected LaAlO3/SrTiO3 Nanostructures", Alexandre Gauthier, Patrick Irvin, Jeremy Levy, APS March Meeting 2014, Denver, CO

"Room-Temperature Electronically-Controlled Ferromagnetism at the LaAlO3/SrTiO3 Interface", Feng Bi, Mengchen Huang, Chung-Wung Bark, Sangwoo Ryu, Chang-Beom Eom, Patrick Irvin, Jeremy Levy, APS March Meeting 2014, Denver, CO

"Emergent Magnetic Phenomena at Complex Oxide Interfaces," Y. Suzuki, Japanese Applied Physics Society Meeting, Kyoto, Japan, September 2013.

"Electron mobility and Magnetotransport in Magnetically Doped LaAlO3/SrTiO3," Y. Suzuki and T. Sanders, Conference on Magnetism and Magnetic Materials, Denver, CO, November 2013.

"Magnetically Doped LaAlO3 Thin Films Grown on SrTiO3 for Modified Quasi-Two Dimensional Electron Gases," Y. Suzuki and M. Gray, Conference on Magnetism and Magnetic Materials, Denver, CO, November 2013

"Emergent Interfacial Ferromagnetism in CaMnO3 Based Superlattices," A. Grutter and Y. Suzuki, American Physical Society Meeting, Denver, CO, March 2014 (given by Alexander Grutter).

"Ruthenium Doped SrTiO3 at the LaAlO3/SrTiO3 Interface for Modified Quasi-Two-Dimensional Electron Gases," M. Gray and Y. Suzuki, Spring 2014 Materials Research Society Meeting, San Francisco, CA April 2014.

"Why is Mobility in LaAlO3/SrTiO3 So Low?," T. Sanders and Y. Suzuki, Spring 2014 Materials Research Society Meeting, San Francisco, CA April 2014

"Spin Torque Oscillators with Perpendicularly Magnetized Layers," A. D. Kent, Current-Driven Magnetization Dynamics Workshop, Leeds, UK

"Electrical Characterization of Spin Torque Nano-oscillators with a Perpendicular Free Layer and In-plane Polarizing Layer," D. Backes, F. Macià and A.D. Kent, 2014 APS March Meeting.

"Stable Magnetic Droplet Solitons in Spin Transfer Nanocontacts,"A. D. Kent, Magnetic Single Nano-Object Workshop and School, September 8-11, 2014, Nancy, France

"Time-resolved x-ray imaging of spin wave dynamics at the nanoscale," Stefano Bonetti, Roopali Kukreja, Hendrik Ohldag, Zhao Chen, Sergei Urazhdin, Josef Frisch, Ferran Macià, Dirk Backes, Anders Eklund, Gunnar Malm, Fred Mancoff, Jordan Katine, Vasyl Tyberkevich, Andrei Slavin, Andrew D. Kent, Joachim Stöhr and Hermann Dürr, 2014 MMM, November 2014.

"XMCD Imaging of Large Angle Spin-Excitations in Spin Transfer Nanocontacts with Perpendicular Anisotropy," Ferran Macia, Dirk Backes, Andrew D. Kent, Stefano Bonetti, Roopali Kukreja and Hendrik Ohldag, 2014 MMM, November 2014.

"Study of Magnetic Droplet Solitons in Spin Transfer Nanocontacts with Perpendicular Magnetic," Anisotropy Sergi Lendinez, Dirk Backes, Andrew D. Kent and Ferran Macia, 2014 MMM, November 2014.

"Effective Spin-Orbit Hamiltonians for Spin Lifetimes and Spin Hall Conductivities of SrTiO3 heterostructures", M. E. Flatté, C. Sahin and G. Vignale, International Workshop on the Functionality of Oxide Interfaces, Kloster Irsee, Germany, March 10, 2014.

"Distinguishing Spin Relaxation Mechanisms in Organic Semiconductors", N. J. Harmon and M. E. Flatté, 58th Annual Conference on Magnetism and Magnetic Materials", Denver, Colorado, November 6, 2013.

"Fringe-field Organic Magnetoresistance", M. E. Flatté, Spin Chemistry Meeting (SCM-2013), Bad Hofgastein, Austria, April 25, 2013.

"Organic magneto-electroluminescence for room temperature transduction between magnetic and optical information", N. Harmon, F. Macia, F. Wang, M. Wohlgenannt, A. D. Kent, and M. E. Flatté, Eighth International Conference on the Physics and Applications of Spin Phenomena in Solids (PASPS VIII), Washington, DC, July 30, 2014.

"Intrinsic spin Hall conductivity in Strontium Titanate and Bismuth Materials", C. Sahin, G. Vignale, and M. E. Flatté, International Conference on Nanoscale Magnetism, Istanbul, Turkey, September 4, 2013.

"Lattice Symmetry Breaking of Spin Wave Propa- gation in Two-Dimensional Magnonic Crystals", G. Sietsema and M. E. Flatté, American Physical Society March Meeting 2014, Denver, Colorado, March 6, 2014.

"Spin Relaxation Theory in Amorphous Silicon and Germanium", N. Harmon and M. E. Flatté, American Physical Society March Meeting

2014, Denver, Colorado, March 3, 2014.

“Magnon Drag in Ferromagnetic Bilayers”, T. Liu, G. Vignale and M. E. Flatté, Spintech VII, Chicago, Illinois, August 1, 2013. (poster).

“Spin Lifetime and Intrinsic Spin Hall Conductivity in SrTiO3 based systems”, C. Sahin, G. Vignale and M. E. Flatté, Spintech VII, Chicago, Illinois, July 31, 2013. (poster).

**Number of Presentations:** 23.00

## Non Peer-Reviewed Conference Proceeding publications (other than abstracts):

| Received | Paper |
|---|---|

**TOTAL:**

**Number of Non Peer-Reviewed Conference Proceeding publications (other than abstracts):**

## Peer-Reviewed Conference Proceeding publications (other than abstracts):

| Received | Paper |
|---|---|

**TOTAL:**

**Number of Peer-Reviewed Conference Proceeding publications (other than abstracts):**

## (d) Manuscripts

| Received | | Paper |
|---|---|---|
| 08/31/2011 | 3.00 | Oleg Chalaev, G. Vignale, M. E. Flatté. Spin-orbit interaction from low-symmetry localized defects in semiconductors, arXiv:1105.5674 (08 2011) |
| 08/31/2011 | 5.00 | F. Wang, F. Macia, M. Wohlgenannt, A. D. Kent, M. E. Flatté. Magnetic fringe field control of electronic transport in an organic film, Submitted to Nature Materials (08 2011) |
| 08/31/2011 | 4.00 | N. J. Harmon, M. E. Flatté. Spin-flip induced magnetoresistance in positionally disordered organic solids, arXiv:1106.3040 (06 2011) |
| 08/31/2012 | 21.00 | Franklin J. Wong, Miaofang Chi, Rajesh V. Chopdekar, Brittany B. Nelson-Cheeseman, Nigel D. Browning, Yuri Suzuki. Potential Barrier Lowering and Electrical Transport at the LaAlO3/SrTiO3 Interface, Submitted to physical review letters (09 2008) |
| 08/31/2012 | 49.00 | Nicholas Harmon, Michael E. Flatté. Magnetoresistance in Organic Semiconductors, SPIE: Optics+Photonics (07 2012) |
| 08/31/2012 | 42.00 | Oleg Chalaev. Matrices, bases and matrix elements for cubic double crystallographic groups, Preprint (06 2012) |
| 08/31/2012 | 35.00 | J. Rybicki, R. Lin, F. Wang, M. Wohlgenannt, C. He, T. Sanders, Y. Suzuki. Tuning the Performance of Organic Spintronic Devices Using X-Ray Generated Traps, Physical Review Letters (accepted) (04 2012) |
| 08/31/2012 | 30.00 | Patrick Irvin, Joshua P. Veazey, Guanglei Cheng, Shicheng Lu, Chung-Wung Bark, Sangwoo Ryu, Chang-Beom Eom, Jeremy Levy. Anomalous High Mobility in LaAlO3/SrTiO3 Nanowires, Nano Letters (07 2012) |
| 08/31/2012 | 29.00 | Joshua P. Veazey, Guanglei Cheng, Patrick Irvin, Cheng Cen, Daniela F. Bogorin, Feng Bi, Mengchen Huang, Chung-Wung Bark, Sangwoo Ryu, Kwang-Hwan Cho, Chang-Beom Eom, Jeremy Levy. Single-Mode Superconductivity , Preprint (07 2012) |
| 08/31/2012 | 28.00 | Guanglei Cheng, Joshua P. Veazey, Patrick Irvin, Cheng Cen, Daniela F. Bogorin, Feng Bi, Mengchen Huang, Shicheng Lu, Chung-Wung Bark, Sangwoo Ryu, Kwang-Hwan Cho, Chang-Beom Eom, Jeremy Levy. Anomalous Hall Effect and Nonlocal Transport in Sketched Oxide Nanostructures, Preprint (07 2012) |
| 08/31/2012 | 27.00 | Guanglei Cheng, Shicheng Lu, Joshua P. Veazey, Patrick Irvin, Feng Bi, Mengchen Huang, Chung-Wung Bark, Sangwoo Ryu, Kwang-Hwan Cho, Chang-Beom Eom, Jeremy Levy. Nonlocal transport in sketched oxide nanostructures, Preprint (07 2012) |
| 08/31/2012 | 26.00 | Vanita Srinivasa, Jeremy Levy. Spatial Analogue of Quantum Spin Dynamics via Spin-Orbit Interaction, ArXiv e-prints (11 2011) |

| | | |
|---|---|---|
| 08/31/2013 | 59.00 | J. P. Veazey, G. Cheng, S. Lu, M. Tomczyk, F. Bi, M. Huang, S. Ryu, C. W. Bark, K. H. Cho, C. B. Eom, P. Irvin, J. Levy. Nonlocal current-voltage characteristics of gated superconducting sketched oxide nanostructures, Europhysics Letters (04 2013) |
| 09/01/2011 | 10.00 | P. Warnicke, D. Bedau, M.-Y. Im, F. Macia, P. Fischer, D. A. Arena, A. D. Kent. Perpendicular magnetic anisotropy in ultrathin Co\|Ni multilayer films studied with ferromagnetic resonance and magnetic x-ray microspectroscopy, Submitted to Journal of Magnetism and Magnetic Materials (09 2011) |
| 09/01/2011 | 18.00 | Cheng Cen, Daniela F. Bogorin, Vanita Srinivasa, Jeremy Levy. Quantum Transport in Oxide Nanostructures, Submitted to physical review letters 1103.036 (09 2011) |
| 09/23/2009 | 1.00 | E. Golovatski, M. Flatte. Spin torque and charge resistance of ferromagnetic semiconductor 2 and domain walls, ( ) |
| 12/05/2011 | 22.00 | Glade Sietsema, Michael Flatté. Magnonic band structure of a two-dimensional magnetic superlattice, (submitted) (11 2011) |
| 12/05/2011 | 23.00 | Elizabeth Golovatski, Michael Flatté. Domain wall attraction and repulsion during spin-torque-induced coherent motion, (submitted) (11 2011) |

**TOTAL:** **18**

**Number of Manuscripts:**

---

## Books

| Received | | Book |
|---|---|---|
| 08/31/2012 | 7.00 | M. Wohlgenannt. Organic magnetoresistance and spin diffusion in organic semiconductor thin film devices, New York: Wiley, (12 2011) |
| 09/10/2012 | 31.00 | Daniela F. Bogorin, Patrick Irvin, Cheng Cen, Jeremy Levy. LaAlO3/SrTiO3-based device concepts, New York: Oxford University Press, (07 2012) |

**TOTAL:** **2**

| Received | Book Chapter |
|---|---|

**TOTAL:**

## Patents Submitted

## Patents Awarded

"Aggregated spin-torque nano-oscillators," F. Hoppenstead, A. D. Kent and F. Macia, files as US Patent Number US8629, 729B2, Issued: January 14, 2014.

## Awards

Ted Sanders, National Science Foundation Predoctoral Fellowship

## Graduate Students

| NAME | PERCENT_SUPPORTED | Discipline |
|---|---|---|
| Matthew Gray | 1.00 | |
| **FTE Equivalent:** | **1.00** | |
| **Total Number:** | **1** | |

## Names of Post Doctorates

| NAME | PERCENT_SUPPORTED |
|---|---|
| **FTE Equivalent:** | |
| **Total Number:** | |

## Names of Faculty Supported

| NAME | PERCENT_SUPPORTED |
|---|---|
| **FTE Equivalent:** | |
| **Total Number:** | |

## Names of Under Graduate students supported

| NAME | PERCENT_SUPPORTED | Discipline |
|---|---|---|
| Matthew Entwistle | 0.00 | Physics |
| **FTE Equivalent:** | **0.00** | |
| **Total Number:** | **1** | |

## Student Metrics

This section only applies to graduating undergraduates supported by this agreement in this reporting period

| | |
|---|---|
| The number of undergraduates funded by this agreement who graduated during this period: ..... | 0.00 |
| The number of undergraduates funded by this agreement who graduated during this period with a degree in science, mathematics, engineering, or technology fields:..... | 0.00 |
| The number of undergraduates funded by your agreement who graduated during this period and will continue to pursue a graduate or Ph.D. degree in science, mathematics, engineering, or technology fields:..... | 0.00 |
| Number of graduating undergraduates who achieved a 3.5 GPA to 4.0 (4.0 max scale):..... | 0.00 |
| Number of graduating undergraduates funded by a DoD funded Center of Excellence grant for Education, Research and Engineering:..... | 0.00 |
| The number of undergraduates funded by your agreement who graduated during this period and intend to work for the Department of Defense ..... | 0.00 |
| The number of undergraduates funded by your agreement who graduated during this period and will receive scholarships or fellowships for further studies in science, mathematics, engineering or technology fields: ..... | 0.00 |

## Names of Personnel receiving masters degrees

| NAME |
|---|
| **Total Number:** |

## Names of personnel receiving PHDs

| NAME |
|---|
| Tianyu Liu |
| Daniel Gopman |
| **Total Number:** 2 |

## Names of other research staff

| NAME | PERCENT_SUPPORTED |
|---|---|
| **FTE Equivalent:** | |
| **Total Number:** | |

## Sub Contractors (DD882)

## Inventions (DD882)

# Scientific Progress

During the final year, which was a no-cost extension, some final projects were brought to completion or further ahead, especially those associated with the oxide effort that had been delayed during Suzuki's relocation to Stanford University.

Imaging spin-wave patterns with XMCD

Using XMCD the emission of spin-wave patterns from a spin torque nanocontact has been directly observed (slide #1 attached). This was one of the main goals of this project. Magnetic soliton propagation can be seen as well, and temporally resolved. This was work done at SLAC in collaboration with Dr. Hendrik Ohldag. We used his scanning x-ray transmission microscope (STXM) at beamline 13-1 to image the excitation patterns in STNO. We focused on the Co L-edge and were able to observe localized spin-waves at the electric contact to a NiCo multilayer film. We are presently analyzing the results and preparing an article on these results for publication. This work represents the first time x-rays have been used to observe spin-waves associated with the spin-transfer interaction.

Organic Magnetoresistance via traps and radical spins

A theory of organic magnetoresistance via traps has been formulated and is in agreement with the experimental measurements previously reported for this MURI by the Wohlgenannt/Suzuki collaboration. The compared results are shown in slide #2, attached. Enhancing the organic magnetoresistance was one of the main goals of this project, and this has now been achieved and explained.

Controlled doping of an organic material using radical spins can suppress the organic magnetoresistance, due to the exchange coupling between the radical spins and the spin transport sites. A new regime, where the radical spin exchange couples strongly with one site of a bottleneck pair, has been demonstrated and the results published in PRB Rapid Communications.

Spin Hall effect in oxides

Collaborative work between Vignale and Flatté has shown that strain at the LaAlO3/SrTiO3 can suppress the spin Hall conductivity, as shown in slide #3 attached. A paper on these results is in preparation for submission, including strain along arbitrary axes.

Suzuki has made significant progress over the past year in understanding the role of disorder in the transport characteristics of LaAlO3/SrTiO3 interfaces through the study of mobility and carrier concentration in doped LaAlO3/SrTiO3 interfaces. Furthermore she has found unexpected long-range antiferromagnetic correlations and structural distortions in CaRuO3/CaMnO3 superlattices that may explain the modulation of the interfacial ferromagnetism with CaMnO3 thickness.

Interfacial ferromagnetism in CaRuO3/CaMnO3 superlattices

Suzuki has performed studies of the structural distortions associated with these superlattices. Detailed analysis of half order peaks in the X-ray diffraction indicates the doubling of the unit cell for superlattices with particular combinations of even and odd CaMnO3 and CaRuO3 layers. The doubling of the unit cell may be correlated with the modulation of the interfacial ferromagnetism that we had observed previously. The interfacial moment alternates between 1μB/interface ion for even CaMnO3 layers and 0.5 μB /interface Mn ion for odd CaMnO3 layers. This modulation may be explained in terms of long-range antiferromagnetic correlation of the bulk of the antiferromagnetic CaMnO3 layers combined with the doubling of the unit cell observed by x-ray diffraction.

Doped quasi-2DEG at the interface of LaAlO3/SrTiO3.

Through her study of rare earth doped LaAlO3 on SrTiO3 interface, Suzuki has discovered that the presence of dopants on the LaAlO3 side of the interface does not significantly affect the mobility, carrier concentration as well as magnetotransport compared to undoped LaAlO3 films. (This is shown on slide #4 attached) The motivation behind the rare earth doping is to insert additional spin-orbit coupling, in the case of Lu, and spin-orbit coupling as well as magnetic moment, in the case of Tm, on the LaAlO3 side of the LaAlO3/SrTiO3 interface. We had previously found that there is (i) an inverse relationship between mobility and carrier concentration that is not consistent with impurity scattering dominated transport and (ii) a steep dependence of the mobility with carrier concentration similar to undoped LaAlO3/SrTiO3. Detailed analysis suggests that mobility and carrier concentration values derived from Hall effect measurements are extremely sensitive to the assumptions associated with the types of carriers. More specifically many groups appear to extract carrier concentration and mobility values by fitting a linear dependence of Hall voltage on magnetic field. Non-linear Hall curves that appear at lower temperatures suggest that perhaps multiband transport is at work. However since there is no unique fit of mobility and carrier values, it is extremely difficult to accurately compare the trends in mobility and carrier concentration. This uncertainty combined with the similarity in doped and undoped samples indicate that transport in this system is dominated by disorder.

Nanoscale control of the metal-insulator transition of the LaAlO3/SrTiO3 interface with a conductive-atomic force microscope (c-

AFM) technique by Levy has enabled a variety of electrical and photonic device concepts and provides a pathway for new types of reconfigurable, oxide-based nanoelectronics. The oxide heterostructure $LaAlO_3/SrTiO_3$ supports a two-dimensional electron liquid with a variety of competing phases, including magnetism, superconductivity, and weak antilocalization because of Rashba spin-orbit coupling. Further confinement of this two-dimensional electron liquid to the quasi-one-dimensional regime can provide insight into the underlying physics of this system and reveal new behavior.

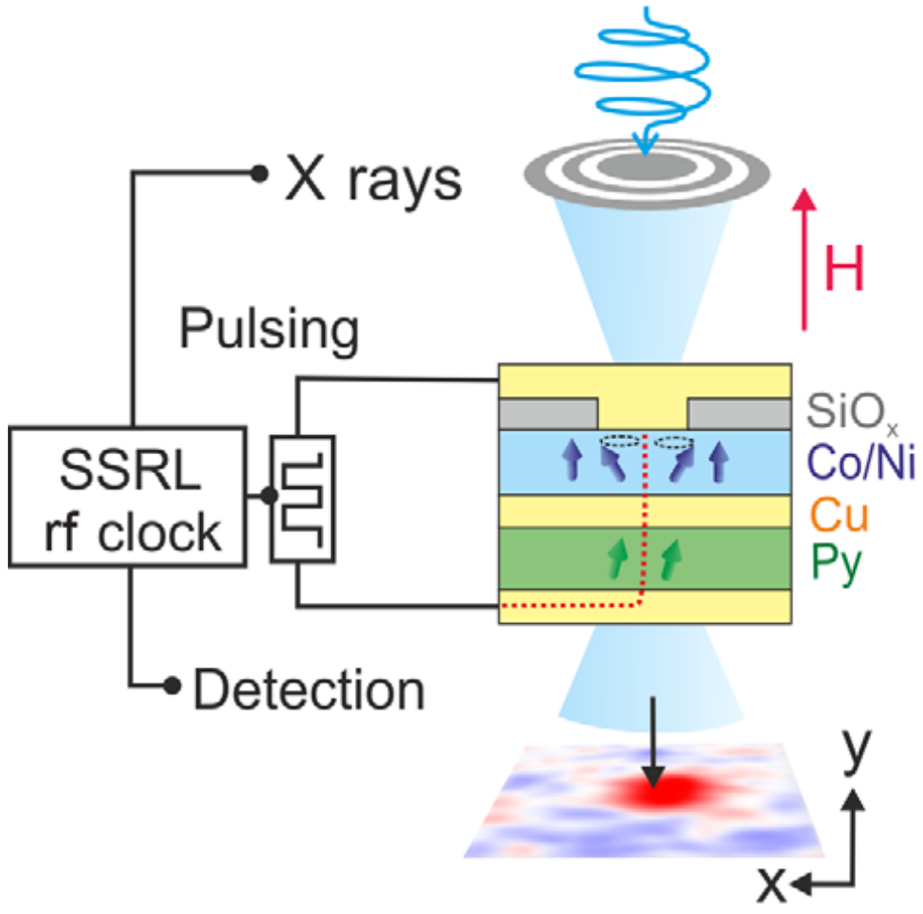
Levy performed transport experiments with nanowire- based single-electron transistors at the interface between $SrTiO_3$ and a thin layer of lanthanum aluminate, $LaAlO_3$. These experiments demonstrate the existence of a robust electronic phase in which electrons pair without forming a superconducting state. Key experimental signatures are captured by a model involving an attractive Hubbard interaction that describes real-space electron pairing as a precursor to superconductivity. Examples of these recent results are shown in the attached slide #5.

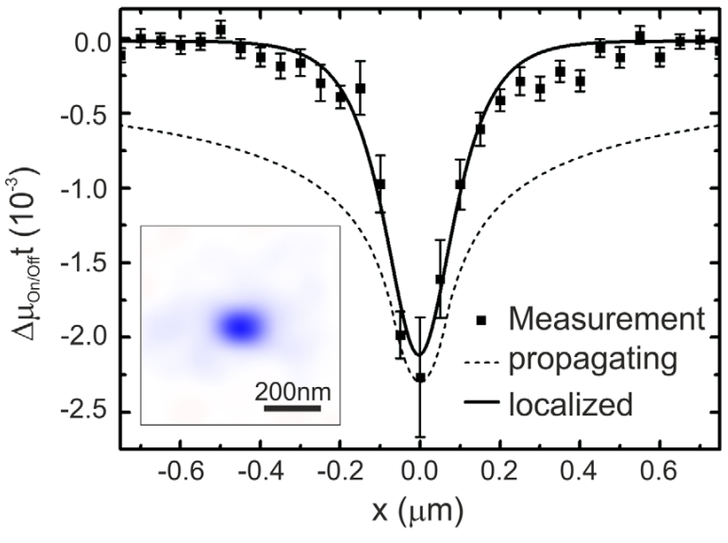
## Technology Transfer

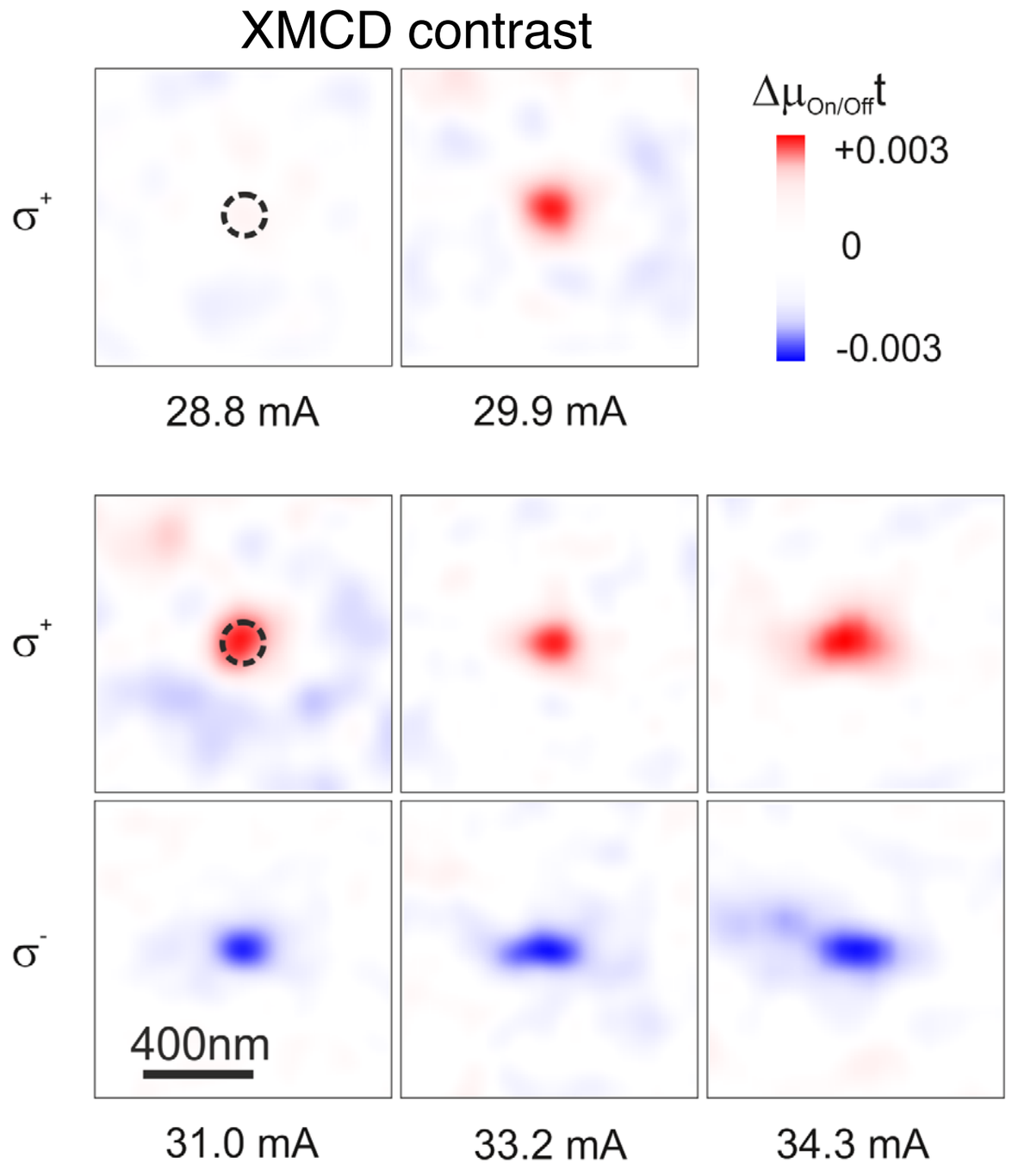
Support has been received from the UI GAP Fund to commercialize the fringe-field magnetoresistive devices. This funding provides support for demonstration of a prototype using thermally-activated delayed fluorescence materials. A start-up company is contemplated to further develop the technology.

# imaging spin-wave patterns using XMCD

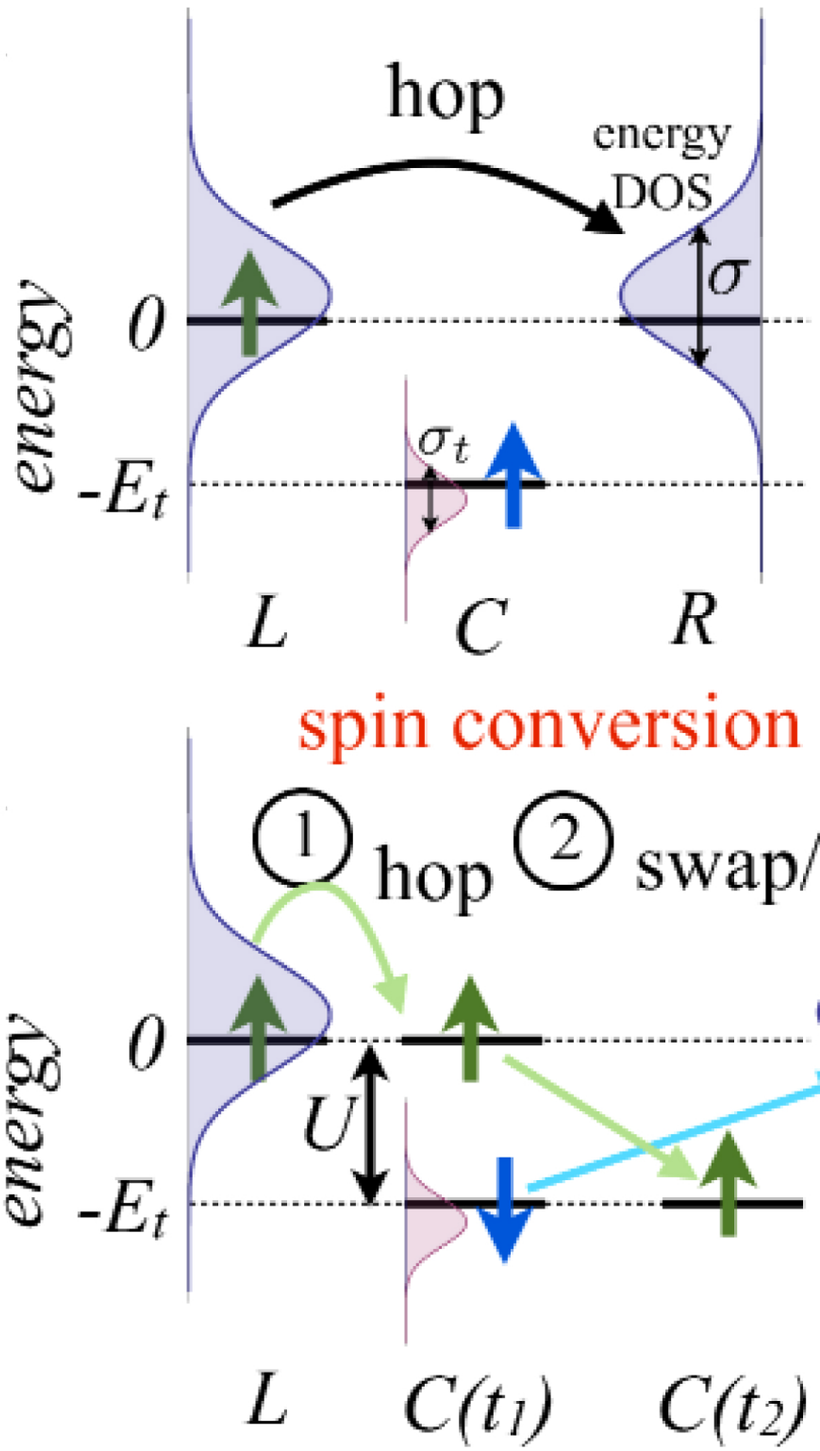
PRL 115, 127205 (2015)



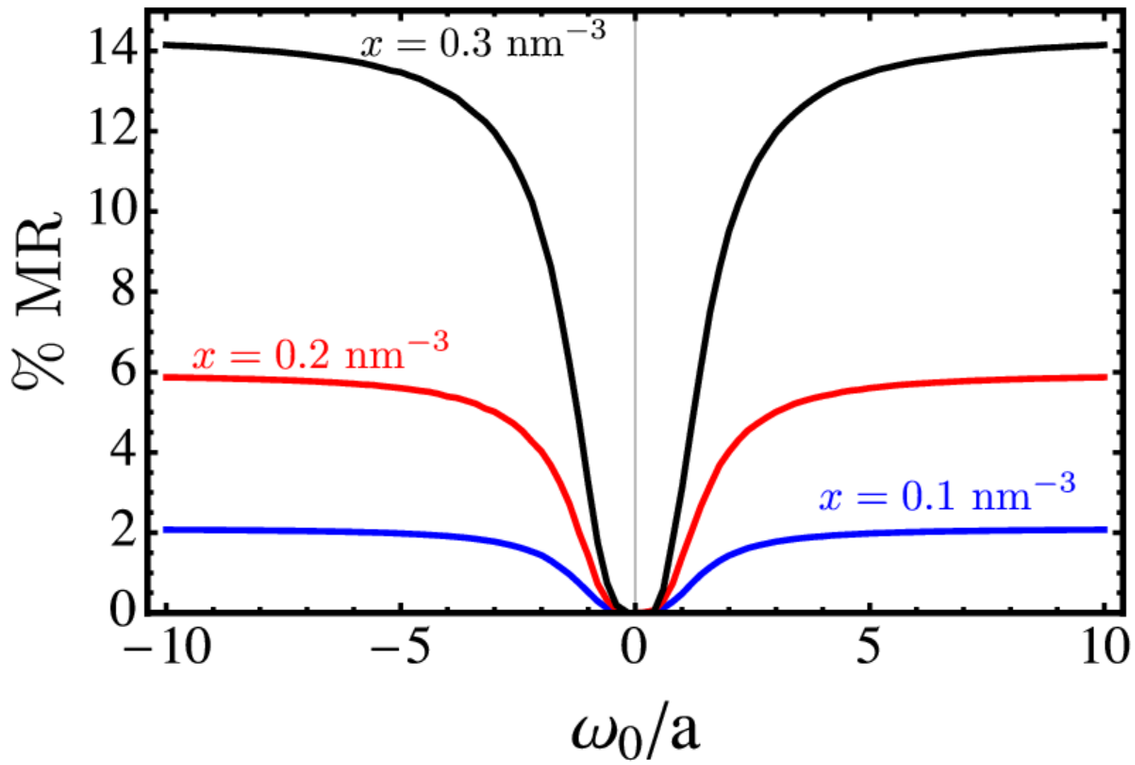



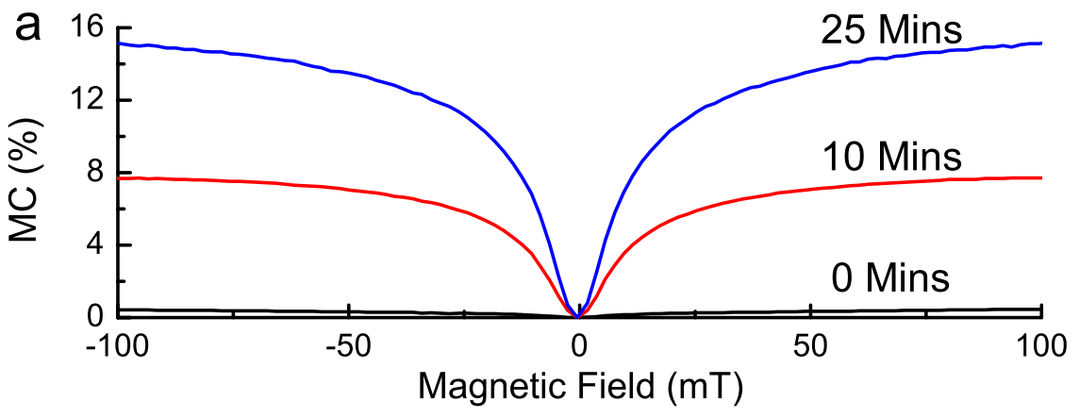
# organic magnetoresistance from traps




theory: JAP 116, 043707 (2014)



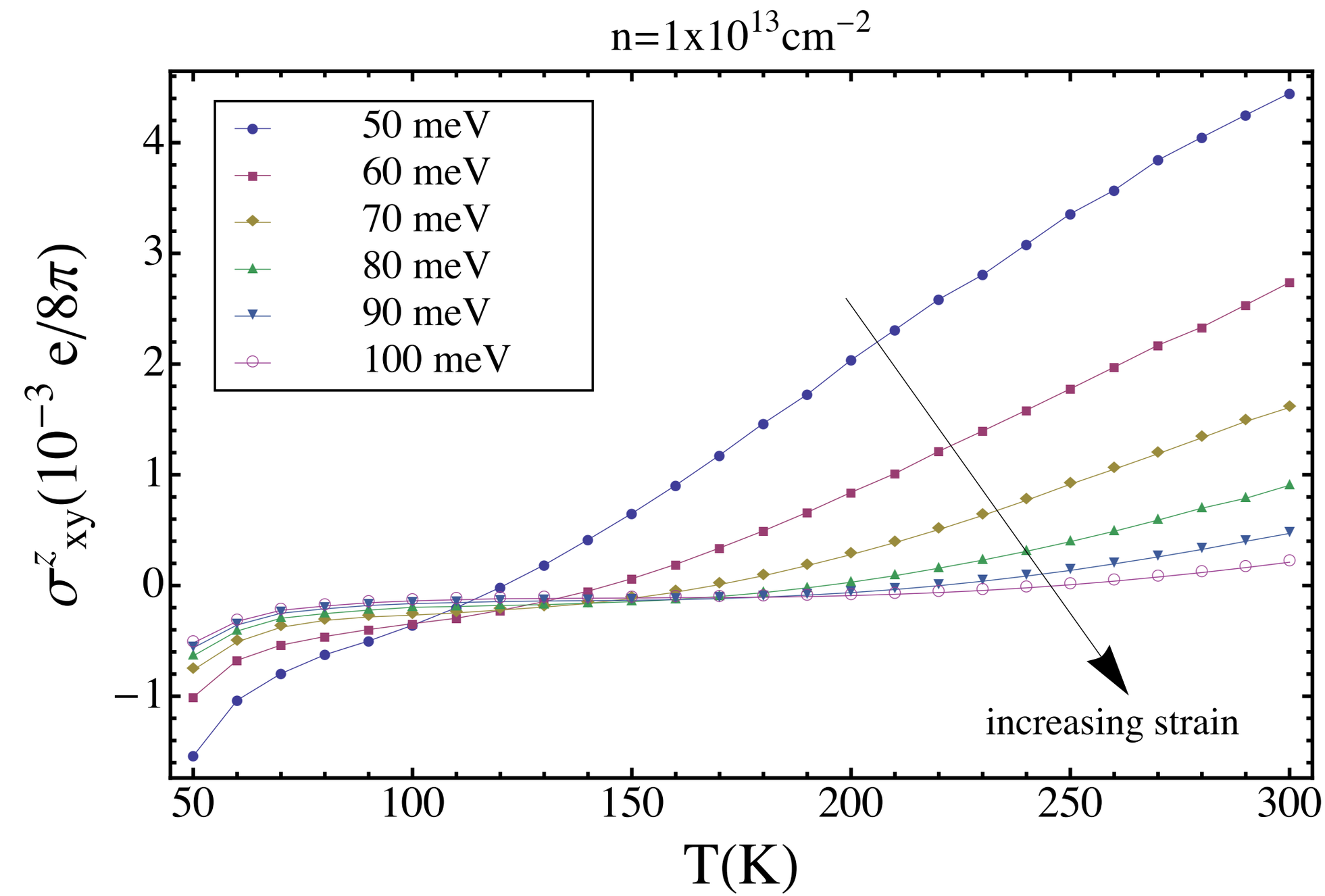

x: concentration of traps




experiment also supported by MURI

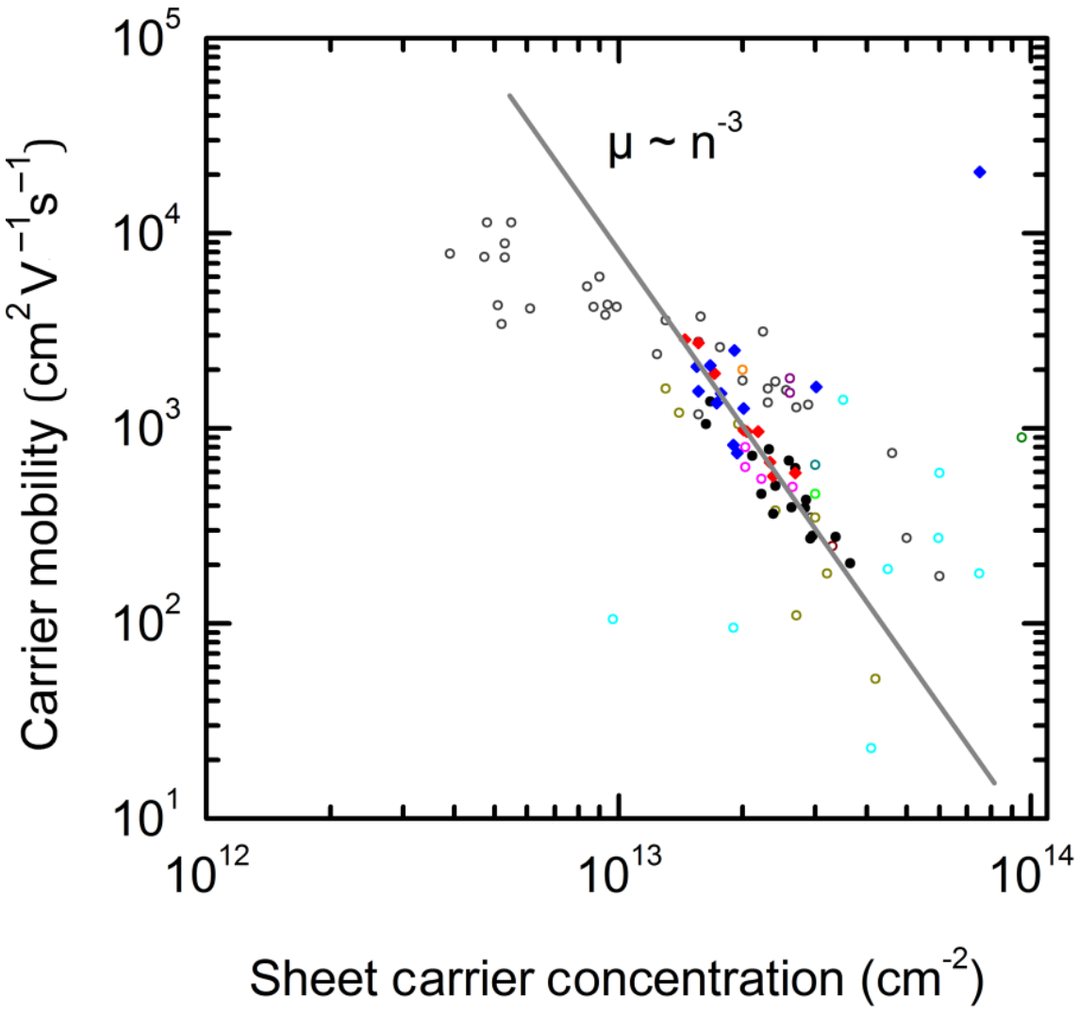
previously published

# strain effect on SHC in STO 2degs




strain splitting reduces Intrinsic Spin Hall Conductivity

# rare-earth doping of LAO/STO



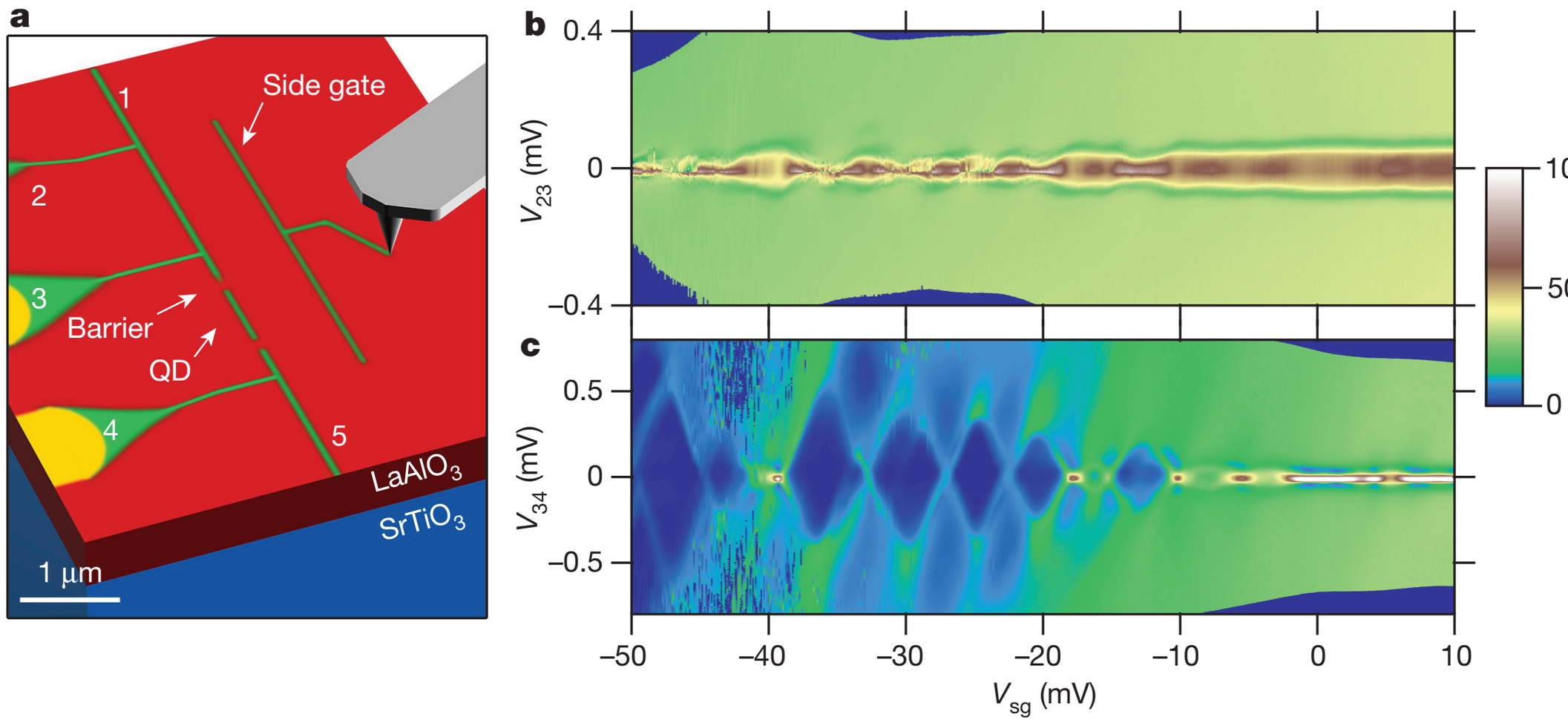

PRB 91, 205112 (2015)

mobility anticorrelated with sheet density - independent of doping character

- ◆ Tm-doped LAO/STO
- ◆ Lu-doped LAO/STO
- • Undoped [this paper and Wong *et al.* (2010)]
- ◦ Annadi *et al.* (2013)
- ◦ Annadi *et al.* (2013)
- ◦ Basletic *et al.* (2008)
- ◦ Bell *et al.* (2009)
- ◦ Ben Shalom *et al.* (2009)
- ◦ Ben Shalom *et al.* (2010)
- ◦ Fix *et al.* (2011)
- ◦ Kalabukhov *et al.* (2008)
- ◦ Shi *et al.* (2013)
- ◦ Xie *et al.* (2013)

# electron pairing without superconductivity

Nature 521, 196 (2015)




schematic of device

demonstration of single-electron transistor behavior in the sketch-FET, and the negative-U model describes the filling. The negative-U is sufficient to pair the electrons on the nanoscale